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20.0.D.2 Materials Readings Heat Transfer Applications Set 2

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form H_2 gas. At the anode, four OH^- ions combine and release O_2 gas, molecular water, and four electrons. The gases produced bubble to the surface, where they can be collected. The standard potential of the water electrolysis cell (when heat is added to the reaction) is a minimum of 1.23 V at 25 °C. The operating potential is actually 1.48 V (or above) in practical electrolysis when heat input is negligible.

Static dielectric constant

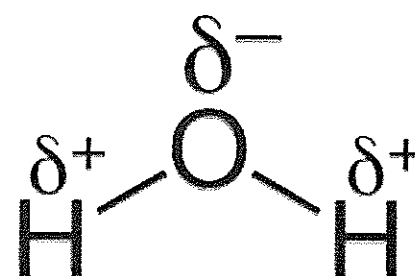
dielectric constant of water

temperature /°C	0	10	20	30	40	50	60	70	80	90	100
ϵ	87.9	83.95	80.18	76.58	73.18	69.88	66.76	63.78	60.93	58.2	55.58

One of the important properties of water is that it has a high dielectric constant. This constant shows its ability to make electrostatic bonds with other molecules, meaning it can eliminate the attraction of the opposite charges of the surrounding ions.

* Polarity and hydrogen bonding

An important feature of water is its polar nature. The structure has a bent molecular geometry for the two hydrogens from the oxygen vertex. The oxygen atom also has two lone pairs of electrons. One effect usually ascribed to the lone pairs is that the H–O–H bend angle is 104.48°,^{[38][39]} which is smaller than the typical tetrahedral angle of 109.47°. The lone pair orbitals are more diffuse than the bond orbitals to the hydrogens; the increased repulsion of the lone pairs forces the O–H bonds closer to each other.^[40]

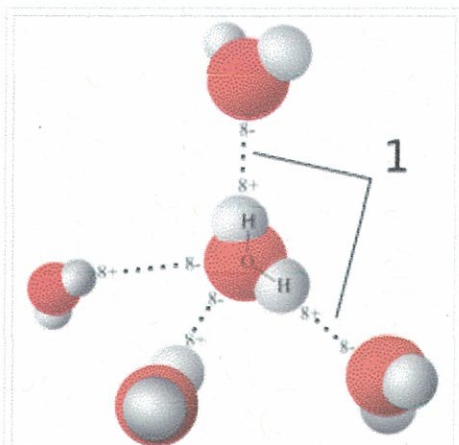


A diagram showing the partial charges on the atoms in a water molecule

Another effect of the electronic structure is that water is a polar molecule. There is a bond dipole moment pointing from each H to the O, making the oxygen partially negative and the hydrogen partially positive. In addition, the O also has nonbonded electrons in the direction opposite the hydrogen atoms. There is thus a large molecular dipole, pointing from a positive region between the two hydrogen atoms to the negative region of the oxygen atom. The charge differences cause water molecules to be attracted to each other (the relatively positive areas being attracted to the relatively negative areas) and to other polar molecules. This attraction contributes to hydrogen bonding, and explains many of the properties of water, such as solvent action.^[41]

A single water molecule can participate in a maximum of four hydrogen bonds because it can accept two bonds using the lone pairs on oxygen and donate two hydrogen atoms. Other molecules like hydrogen fluoride, ammonia and methanol can also form hydrogen bonds. However they do not show anomalous thermodynamic, kinetic or structural properties like those observed in water. The answer to the apparent difference between water and other hydrogen bonding liquids lies in the fact that apart from water none of these examples participate in four hydrogen bonds; this is either due to an inability to donate or accept hydrogens or is due to steric effects in bulky residues. In water, intermolecular tetrahedral order due to the four hydrogen bonds gives rise to an open structure and a 3-dimensional bonding network, resulting in the anomalous decrease of density when cooled below 4 °C.

Although hydrogen bonding is a relatively weak attraction compared to the covalent bonds within the water



Model of hydrogen bonds (1) between molecules of water

molecule itself, it is responsible for a number of water's physical properties. One such property is its relatively high melting and boiling point temperatures; more energy is required to break the hydrogen bonds between water molecules. In contrast, hydrogen sulfide (H_2S), has much weaker hydrogen bonding due to sulfur's lower electronegativity. H_2S is a gas at room temperature, in spite of hydrogen sulfide having nearly two times the molar mass of water. The extra bonding between water molecules also gives liquid water a large specific heat capacity. This high heat capacity makes water a good heat storage medium (coolant) and heat shield.

Cohesion and adhesion

Water molecules stay close to each other (cohesion), due to

the collective action of hydrogen bonds between water molecules. These hydrogen bonds are constantly breaking, with new bonds being formed with different water molecules; but at any given time in a sample of liquid water, a large portion of the molecules are held together by such bonds.^[42]

Water also has high adhesion properties because of its polar nature. On extremely clean/smooth glass the water may form a thin film because the molecular forces between glass and water molecules (adhesive forces) are stronger than the cohesive forces. In biological cells and organelles, water is in contact with membrane and protein surfaces that are hydrophilic; that is, surfaces that have a strong attraction to water. Irving Langmuir observed a strong repulsive force between hydrophilic surfaces. To dehydrate hydrophilic surfaces—to remove the strongly held layers of water of hydration—requires doing substantial work against these forces, called hydration forces. These forces are very large but decrease rapidly over a nanometer or less.^[43] They are important in biology, particularly when cells are dehydrated by exposure to dry atmospheres or to extracellular freezing.^[44]



Dew drops adhering to a spider web

Surface tension

Water has a high surface tension of 72.8 mN/m at room temperature, caused by the strong cohesion between water molecules, the highest of the common non-ionic, non-metallic liquids. This can be seen when small quantities of water are placed onto a sorption-free (non-adsorbent and non-absorbent) surface, such as polyethylene or Teflon, and the water stays together as drops. Just as significantly, air trapped in surface disturbances forms bubbles, which sometimes last long enough to transfer gas molecules to the water.

Another surface tension effect is capillary waves, which are the surface ripples that form around the impacts of drops on water surfaces, and sometimes occur with strong subsurface currents flowing to the water surface. The apparent elasticity caused by surface tension drives the waves.

Capillary action

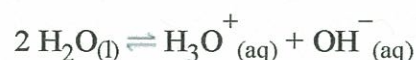
Due to an interplay of the forces of adhesion and surface tension, water exhibits capillary action whereby

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Water is primarily a liquid under standard conditions, which is not predicted from its relationship to other analogous hydrides of the oxygen family in the periodic table, which are gases such as hydrogen sulfide. The elements surrounding oxygen in the periodic table, nitrogen, fluorine, phosphorus, sulfur and chlorine, all combine with hydrogen to produce gases under standard conditions. The reason that water forms a liquid is that oxygen is more electronegative than all of these elements with the exception of fluorine. Oxygen attracts electrons much more strongly than hydrogen, resulting in a net positive charge on the hydrogen atoms, and a net negative charge on the oxygen atom. The presence of a charge on each of these atoms gives each water molecule a net dipole moment. Electrical attraction between water molecules due to this dipole pulls individual molecules closer together, making it more difficult to separate the molecules and therefore raising the boiling point. This attraction is known as hydrogen bonding. The molecules of water are constantly moving in relation to each other, and the hydrogen bonds are continually breaking and reforming at timescales faster than 200 femtoseconds.^[18] However, this bond is sufficiently strong to create many of the peculiar properties of water, such as those that make it integral to life. Water can be described as a polar liquid that slightly dissociates disproportionately into the hydronium ion ($\text{H}_3\text{O}^+_{(\text{aq})}$) and an associated hydroxide ion ($\text{OH}^-_{(\text{aq})}$).



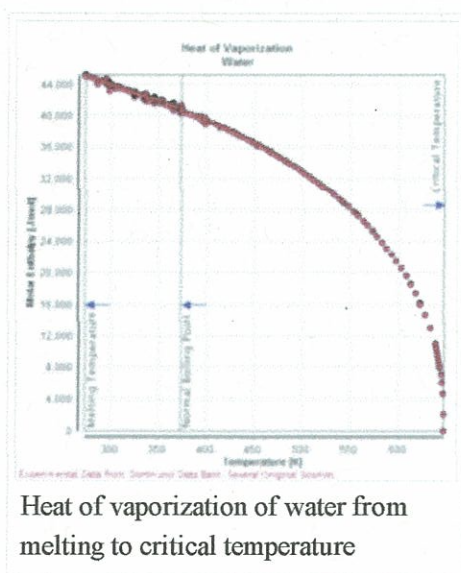
The dissociation constant for this dissociation is commonly symbolized as K_w and has a value of about 10^{-14} at 25 °C; see "Water (data page)" and "Self-ionization of water" for more information.

Percentage of elements in water by mass: 11.1% hydrogen, 88.9% oxygen.

The self-diffusion coefficient of water is $2.299 \cdot 10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$.^[19]

Water, ice, and vapor

Heat capacity and heats of vaporization and fusion



Water has a very high specific heat capacity – the second highest among all the heteroatomic species (after ammonia), as well as a high heat of vaporization (40.65 kJ/mol or 2257 kJ/kg at the normal boiling point), both of which are a result of the extensive hydrogen bonding between its molecules. These two unusual properties allow water to moderate Earth's climate by buffering large fluctuations in temperature.

According to Josh Willis, of NASA's Jet Propulsion Laboratory, the oceans absorb one thousand times more heat than the atmosphere

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(air) and are holding 80 to 90% of the heat of global warming.^[21]

The specific enthalpy of fusion of water is 333.55 kJ/kg at 0 °C, i.e. melting ice absorbs the same energy as ice warming from -160 degrees Celsius up to its melting point. Of common substances, only that of ammonia is higher. This property confers resistance to melting on the ice of glaciers and drift ice. Before and since the advent of mechanical refrigeration, ice was and still is in common use for retarding food spoilage.

Constant-pressure heat capacity	
Temperature (°C)	<i>C</i> _p (J/(g·K) at 100 kPa) ^[7]
0	4.2176
10	4.1921
20	4.1818
25	4.1814
30	4.1784
40	4.1785
50	4.1806
60	4.1843
70	4.1895
80	4.1963
90	4.205
100	4.2159

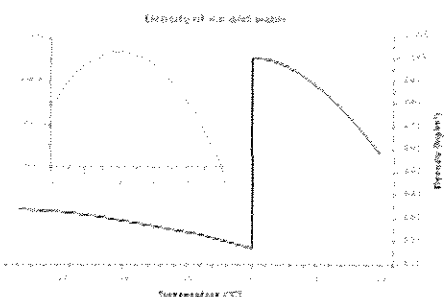
Heat of vaporization	
Temperature (°C)	<i>H</i> _v (kJ/mol) ^[20]
0	45.054
25	43.99
40	43.35
60	42.482
80	41.585
100	40.657
120	39.684
140	38.643
160	37.518
180	36.304
200	34.962
220	33.468
240	31.809
260	29.93
280	27.795
300	25.3
320	22.297
340	18.502
360	12.966
374	2.066

Note that the specific heat capacity of ice at −10 °C is about 2.05 J/(g·K) and that the heat capacity of steam at 100 °C is about 2.080 J/(g·K).

Density of water and ice

The density of water is approximately one gram per cubic centimeter. It is dependent on its temperature, but the relation is not linear and is unimodal rather than monotonic (see table at left). When cooled from room temperature liquid water becomes increasingly dense, as with other substances, but at approximately 4 °C (39 °F), pure water reaches its maximum density. As it is cooled further, it expands to become less dense. This unusual negative thermal expansion is attributed to strong, orientation-dependent, intermolecular interactions and is also observed in molten silica.^[24]

The solid form of most substances is denser than the liquid phase; thus, a block of most solids will sink in the liquid. However, a block



Density of ice and water as a function of temperature

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Density of liquid water

Temp (°C)	Density (kg/m³) ^{[22][23]}
+100	958.4
+80	971.8
+60	983.2
+40	992.2
+30	995.6502
+25	997.0479
+22	997.7735
+20	998.2071
+15	999.1026
+10	999.7026
+4	999.9720
0	999.8395
−10	998.117
−20	993.547
−30	983.854

The values below 0 °C refer to supercooled water.

of ice floats in liquid water because ice is *less* dense. Upon freezing, the density of water decreases by about 9%.^[25] This is due to the 'cooling' of intermolecular vibrations allowing the molecules to form steady hydrogen bonds with their neighbors and thereby gradually locking into positions reminiscent of the hexagonal packing achieved upon freezing to ice I_h. Whereas the hydrogen bonds are shorter in the crystal than in the liquid, this locking effect reduces the average coordination number of molecules as the liquid approaches nucleation. Other substances that expand on freezing are silicon, gallium, germanium, antimony, bismuth, plutonium and also chemical compounds that form spacious crystal lattices with tetrahedral coordination.

Only ordinary hexagonal ice is less dense than the liquid. Under increasing pressure, ice undergoes a number of transitions to other allotropic forms with higher density than liquid water, such as ice II, ice III, high-density amorphous ice (HDA), and very-high-density amorphous ice (VHDA).

Water also expands significantly as the temperature increases. Water near the boiling point is about 96% as dense as water at 4 °C.

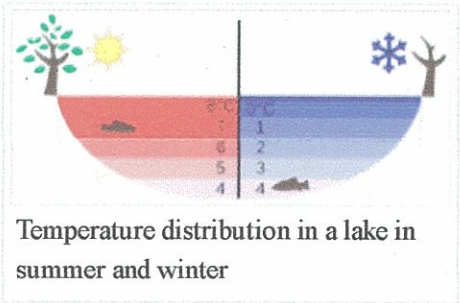
The melting point of ice is 0 °C (32 °F, 273.15 K) at standard pressure, however, pure liquid water can be supercooled well below that temperature without freezing if the liquid is not

mechanically disturbed. It can remain in a fluid state down to its homogeneous nucleation point of approximately 231 K (−42 °C).^[26] The melting point of ordinary hexagonal ice falls slightly under moderately high pressures, but as ice transforms into its allotropes (see crystalline states of ice) above 209.9 MPa (2,072 atm), the melting point increases markedly with pressure, i.e., reaching 355 K (82 °C) at 2.216 GPa (21,870 atm) (triple point of Ice VII^[27]).

A significant increase of pressure is required to lower the melting point of ordinary ice—the pressure exerted by an ice skater on the ice only reduces the melting point by approximately 0.09 °C (0.16 °F).

These properties of water have important consequences in its role in Earth's ecosystem. Water at a temperature of 4 °C (39.2 °F) will always accumulate at the bottom of freshwater lakes, irrespective of the temperature in the atmosphere.

In cold countries, when the temperature of fresh water reaches 4 °C, the layers of water near the top in contact with cold air continue to lose heat energy and their temperature falls below 4 °C. On cooling below 4 °C, these layers do not sink as fresh water has a maximum density at 4 °C. (Refer: Polarity and hydrogen bonding) Due to this, the layer of water at 4 °C remains at the bottom and above this layers of water 3 °C, 2 °C, 1 °C and 0 °C are formed. As water at 0 °C is the least dense it floats on the top and turns into ice as the water continues to cool. Ice growth continues on the bottom of the ice as

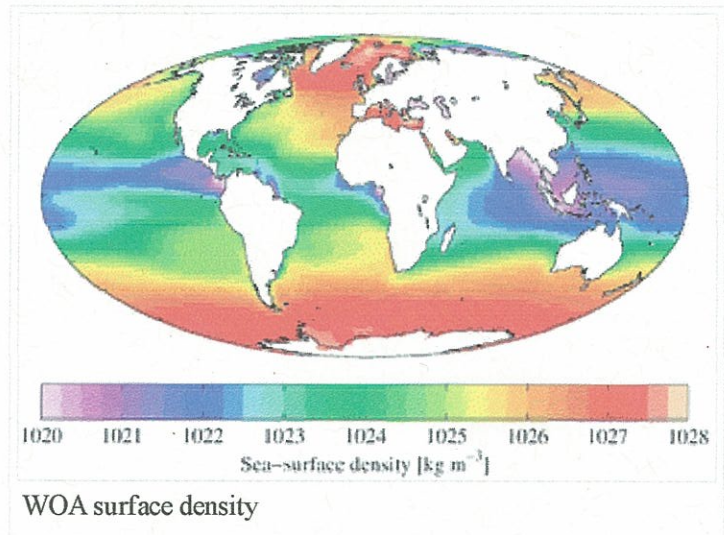


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heat is drawn away through the ice (the heat conductivity of ice is similar to glass). All the while the water further down below the ice is still 4 °C. As the ice layer shields the lake from the effect of the wind, water in the lake will no longer turn over. Although both water and ice are relatively good conductors of heat, a thick layer of ice and a thick layer of stratified water under the ice slow down further heat loss from the lake relative to when the lake was exposed. It is, therefore, unlikely that sufficiently deep lakes will freeze completely, unless stirred by strong currents that mix cooler and warmer water and accelerate the cooling. Thus, as long as the pond or lake does not freeze up completely, aquatic creatures are not exposed to freezing temperatures. In warming weather, chunks of ice float, rather than sink to the bottom where they might melt extremely slowly. These properties therefore allow aquatic life in the lake to survive during the winter.

Density of saltwater and ice

The density of water is dependent on the dissolved salt content as well as the temperature of the water. Ice still floats in the oceans, otherwise they would freeze from the bottom up. However, the salt content of oceans lowers the freezing point by about 2 °C (see here for explanation) and lowers the temperature of the density maximum of water to the freezing point. This is why, in ocean water, the downward convection of colder water is *not* blocked by an expansion of water as it becomes colder near the freezing point. The oceans' cold water near the freezing point continues to sink. For this reason, any creature attempting to survive at the bottom of such cold water as the Arctic Ocean generally lives in water that is 4 °C colder than the temperature at the bottom of frozen-over fresh water lakes and rivers in the winter.



As the surface of salt water begins to freeze (at −1.9 °C for normal salinity seawater, 3.5%) the ice that forms is essentially salt free with a density approximately equal to that of freshwater ice. This ice floats on the surface and the salt that is "frozen out" adds to the salinity and density of the seawater just below it, in a process known as *brine rejection*. This denser saltwater sinks by convection and the replacing seawater is subject to the same process. This provides essentially freshwater ice at −1.9 °C on the surface. The increased density of the seawater beneath the forming ice causes it to sink towards the bottom. On a large scale, the process of brine rejection and sinking cold salty water results in ocean currents forming to transport such water away from the Poles, leading to a global system of currents called the thermohaline circulation.

Miscibility and condensation

Water is miscible with many liquids, for example ethanol in all proportions, forming a single homogeneous liquid. On the other hand, water and most oils are *immiscible* usually forming layers according to increasing density from the top.

As a gas, water vapor is completely miscible with air. On the other hand the maximum water vapor pressure that is thermodynamically stable with the liquid (or solid) at a given temperature is relatively low compared with total atmospheric pressure. For example, if the vapor *partial pressure*^[28] is 2% of atmospheric pressure

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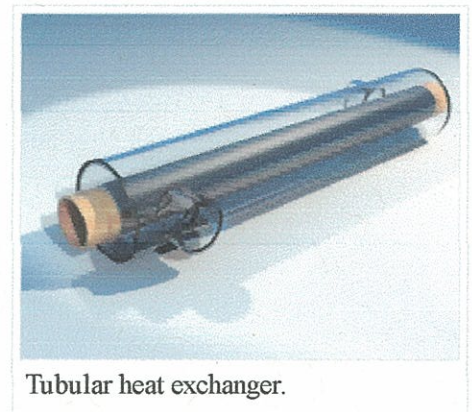
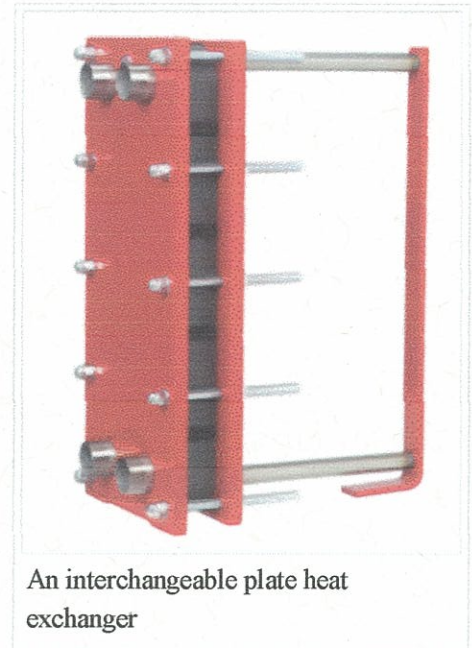
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Heat exchanger

From Wikipedia, the free encyclopedia

A **heat exchanger** is a piece of equipment built for efficient heat transfer from one medium to another. The media may be separated by a solid wall to prevent mixing or they may be in direct contact.^[1] They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment. The classic example of a heat exchanger is found in an internal combustion engine in which a circulating fluid known as engine coolant flows through radiator coils and air flows past the coils, which cools the coolant and heats the incoming air.



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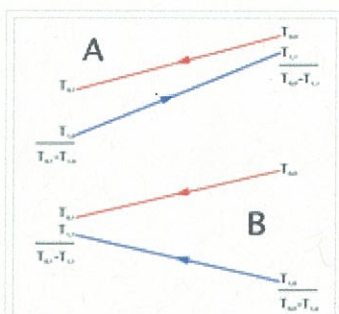
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Flow arrangement



Countercurrent (A) and parallel (B) flows

There are three primary classifications of heat exchangers according to their flow arrangement. In

parallel-flow heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In *counter-flow* heat exchangers the fluids enter the exchanger from opposite ends. The counter current design is the most efficient, in that it can transfer the most heat from the heat (transfer) medium per unit mass due to the fact that the average temperature difference along any unit length is *higher*. See countercurrent exchange. In a *cross-flow* heat exchanger, the fluids travel roughly perpendicular to one another through the exchanger.

For efficiency, heat exchangers are designed to maximize the surface area of the wall between the two fluids, while minimizing resistance to fluid flow through the exchanger. The exchanger's performance can also be

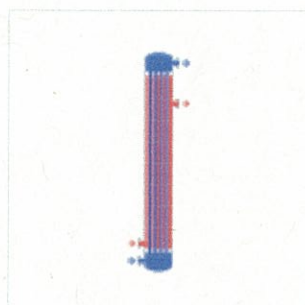


Fig. 1: Shell and tube heat exchanger, single pass (1–1 parallel flow)

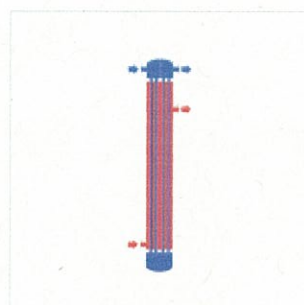


Fig. 2: Shell and tube heat exchanger, 2-pass tube side (1–2 crossflow)

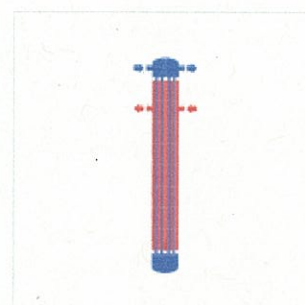


Fig. 3: Shell and tube heat exchanger, 2-pass shell side, 2-pass tube side (2–2 countercurrent)

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affected by the addition of fins or corrugations in one or both directions, which increase surface area and may channel fluid flow or induce turbulence.

The driving temperature across the heat transfer surface varies with position, but an appropriate mean temperature can be defined. In most simple systems this is the "log mean temperature difference" (LMTD). Sometimes direct knowledge of the LMTD is not available and the NTU method is used.

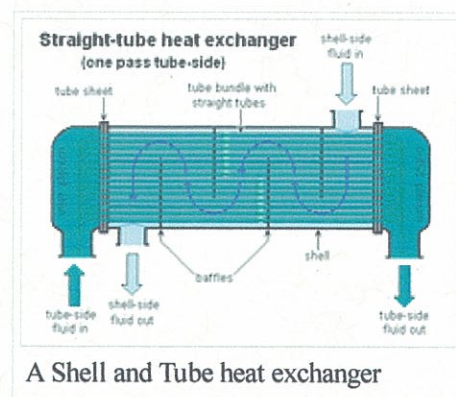
Types of heat exchangers

Double pipe heat exchangers are the simplest exchangers used in industries. On one hand, these heat exchangers are cheap for both design and maintenance, making them a good choice for small industries. On the other hand, their low efficiency coupled with the high space occupied in large scales, has led modern industries to use more efficient heat exchangers like shell and tube or plate. However, since double pipe heat exchangers are simple, they are used to teach heat exchanger design basics to students as the fundamental rules for all heat exchangers are the same. To start the design of a double pipe heat exchanger, the first step is to calculate the heat duty of the heat exchanger. It must be noted that for easier design, it's better to ignore heat loss to the environment for initial design.

Shell and tube heat exchanger

Shell and tube heat exchangers consist of series of tubes. One set of these tubes contains the fluid that must be either heated or cooled. The second fluid runs over the tubes that are being heated or cooled so that it can either provide the heat or absorb the heat required. A set of tubes is called the tube bundle and can be made up of several types of tubes: plain, longitudinally finned, etc. Shell and tube heat exchangers are typically used for high-pressure applications (with pressures greater than 30 bar and temperatures greater than 260 °C).^[2] This is because the shell and tube heat exchangers are robust due to their shape.

Several thermal design features must be considered when designing the tubes in the shell and tube heat exchangers: There can be many variations on the shell and tube design. Typically, the ends of each tube are connected to plenums (sometimes called water boxes) through holes in tubesheets. The tubes may be straight or bent in the shape of a U, called U-tubes.



- **Tube diameter:** Using a small tube diameter makes the heat exchanger both economical and compact. However, it is more likely for the heat exchanger to foul up faster and the small size makes mechanical cleaning of the fouling difficult. To prevail over the fouling and cleaning problems, larger tube diameters can be used. Thus to determine the tube diameter, the available space, cost and fouling nature of the fluids must be considered.
- **Tube thickness:** The thickness of the wall of the tubes is usually determined to ensure:
 - There is enough room for corrosion
 - That flow-induced vibration has resistance
 - Axial strength

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in heat exchangers).

Plate heat exchanger

Another type of heat exchanger is the plate heat exchanger. One is composed of multiple, thin, slightly separated plates that have very large surface areas and small fluid flow passages for heat transfer. This stacked-plate arrangement typically has lower volume and cost than the shell and tube heat exchanger. Advances in gasket and brazing technology have made the plate-type heat exchanger increasingly practical. In HVAC applications, large heat exchangers of this type are called *plate-and-frame*; when used in open loops, these heat exchangers are normally of the gasket type to allow periodic disassembly, cleaning, and inspection. There are many types of permanently bonded plate heat exchangers, such as dip-brazed, vacuum-brazed, and welded plate varieties, and they are often specified for closed-loop applications such as refrigeration. Plate heat exchangers also differ in the types of plates that are used, and in the configurations of those plates. Some plates may be stamped with "chevron", dimpled, or other patterns, where others may have machined fins and/or grooves.

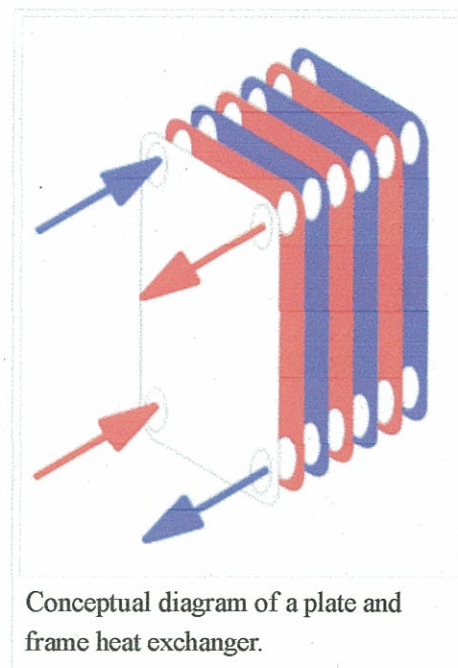
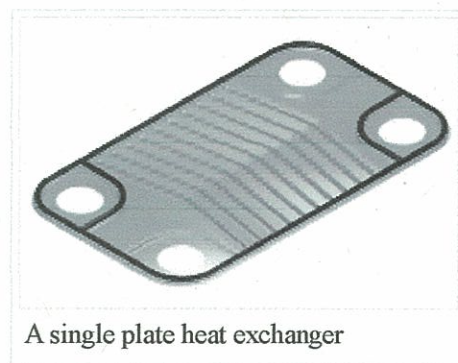


Plate and shell heat exchanger

A third type of heat exchanger is a plate and shell heat exchanger, which combines plate heat exchanger with shell and tube heat exchanger technologies. The heart of the heat exchanger contains a fully welded circular plate pack made by pressing and cutting round plates and welding them together. Nozzles carry flow in and out of the platepack (the 'Plate side' flowpath). The fully welded platepack is assembled into an outer shell that creates a second flowpath (the 'Shell side'). Plate and shell technology offers high heat transfer, high pressure, high operating temperature, compact size, low fouling and close approach temperature. In particular, it does completely without gaskets, which provides security against leakage at high pressures and temperatures.



Adiabatic wheel heat exchanger

A fourth type of heat exchanger uses an intermediate fluid or solid store to hold heat, which is then moved to the other side of the heat exchanger to be released. Two examples of this are adiabatic wheels, which consist of a large wheel with fine threads rotating through the hot and cold fluids, and fluid heat exchangers.

Plate fin heat exchanger

This type of heat exchanger uses "sandwiched" passages containing fins to increase the effectiveness of the unit. The designs include crossflow and counterflow coupled with various fin configurations such as straight fins, offset fins and wavy fins.

Plate and fin heat exchangers are usually made of aluminium alloys, which provide high heat transfer

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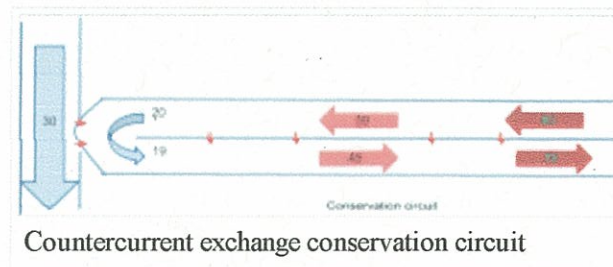
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weather.

In species that have external testes (such as humans), the artery to the testis is surrounded by a mesh of veins called the pampiniform plexus. This cools the blood heading to the testis, while reheating the returning blood.

Birds, fish, marine mammals

"Countercurrent" heat exchangers occur naturally in the circulation system of fish, whales and other marine mammals. Arteries to the skin carrying warm blood are intertwined with veins from the skin carrying cold blood, causing the warm arterial blood to exchange heat with the cold venous blood. This reduces the overall heat loss in cold waters. Heat exchangers are also present in the tongue of baleen whales as large volumes of water flow through their mouths.^{[29][30]} Wading birds use a similar system to limit heat losses from their body through their legs into the water.



Carotid rete

The carotid rete is a counter-current heat exchanging organ in some ungulates. The blood ascending the carotid arteries on its way to the brain, flows via a network of vessels where heat is discharged to the veins of cooler blood descending from the nasal passages. The carotid rete allows Thomson's gazelle to maintain its brain almost 3 °C cooler than the rest of the body, and therefore aids in tolerating bursts in metabolic heat production such as associated with outrunning cheetahs (during which the body temperature exceeds the maximum temperature at which the brain could function).^[31]

In industry

Heat exchangers are widely used in industry both for cooling and heating large scale industrial processes. The type and size of heat exchanger used can be tailored to suit a process depending on the type of fluid, its phase, temperature, density, viscosity, pressures, chemical composition and various other thermodynamic properties.

In many industrial processes there is waste of energy or a heat stream that is being exhausted, heat exchangers can be used to recover this heat and put it to use by heating a different stream in the process. This practice saves a lot of money in industry, as the heat supplied to other streams from the heat exchangers would otherwise come from an external source that is more expensive and more harmful to the environment.

Heat exchangers are used in many industries, including:

- Waste water treatment
- Refrigeration
- Wine and beer making
- Petroleum refining

In waste water treatment, heat exchangers play a vital role in maintaining optimal temperatures within

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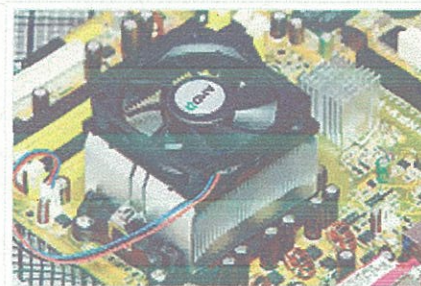
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Heat sink

From Wikipedia, the free encyclopedia

In electronic systems, a **heat sink** is a passive heat exchanger that cools a device by dissipating heat into the surrounding medium. In computers, heat sinks are used to cool central processing units or graphics processors. Heat sinks are used with high-power semiconductor devices such as power transistors and optoelectronics such as lasers and light emitting diodes (LEDs), where the heat dissipation ability of the basic device is insufficient to moderate its temperature.

A heat sink is designed to maximize its surface area in contact with the cooling medium surrounding it, such as the air. Air velocity, choice of material, protrusion design and surface treatment are factors that affect the performance of a heat sink. Heat sink attachment methods and thermal interface materials also affect the die temperature of the integrated circuit. Thermal adhesive or thermal grease improve the heat sink's performance by filling air gaps between the heat sink and the heat spreader on the device.



A fan-cooled heat sink on the processor of a personal computer. To the right is a smaller heat sink cooling another integrated circuit of the motherboard.

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Heat transfer principle

A heat sink transfers thermal energy from a higher temperature device to a lower temperature fluid medium. The fluid medium is frequently air, but can also be water, refrigerants or oil. If the fluid medium is water, the heat sink is frequently called a cold plate. In thermodynamics a heat sink is a heat reservoir that can absorb an arbitrary amount of heat without significantly changing temperature. Practical heat sinks for electronic devices must have a temperature higher than the surroundings to transfer heat by convection, radiation, and conduction. The power supplies of electronics are not 100% efficient, so extra heat is produced that may be detrimental to the function of the device. As such, a heat sink is included in the design to disperse heat to improve efficient energy use.^[1]

To understand the principle of a heat sink, consider Fourier's law of heat conduction. Fourier's law of heat conduction, simplified to a one-dimensional form in the x -direction, shows that when there is a temperature gradient in a body, heat will be transferred from the higher temperature region to the lower temperature region. The rate at which heat is transferred by conduction, q_k , is proportional to the product of the temperature gradient and the cross-sectional area through which heat is transferred.

$$q_k = -kA \frac{dT}{dx}$$

Consider a heat sink in a duct, where air flows through the duct, as shown in Figure 2. It is assumed that the heat sink base is higher in temperature than the air. Applying the conservation of energy, for steady-state conditions, and Newton's law of cooling to the temperature nodes shown in Figure 2 gives the following set of equations:

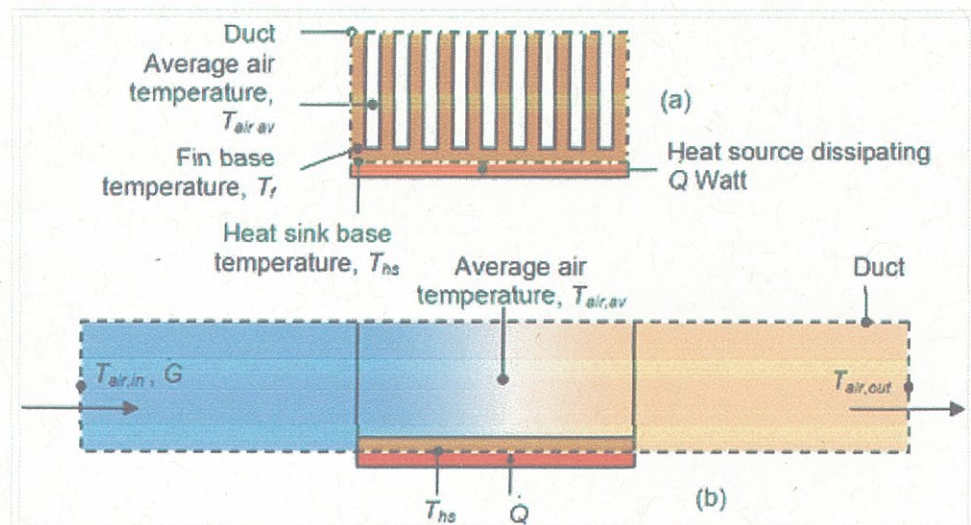


Figure 2: Sketch of a heat sink in a duct used to calculate the governing equations from conservation of energy and Newton's law of cooling.

$$\dot{Q} = \dot{m}c_{p,in}(T_{air,out} - T_{air,in}) \quad (1)$$

$$\dot{Q} = \frac{T_{hs} - T_{air,av}}{R_{hs}} \quad (2)$$

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between 0.5 up to 1.7 °C/W, depending on the case size, and use of grease or insulating mica washer.^[3]

Material

The most common heat sink materials are aluminium alloys.^[5] Aluminium alloy 1050A has one of the higher thermal conductivity values at 229 W/m•K^[6] but is mechanically soft. Aluminium alloys 6061 and 6063 are commonly used, with thermal conductivity values of 166 and 201 W/m•K, respectively. The values depend on the temper of the alloy.

Copper has excellent heat sink properties in terms of its thermal conductivity, corrosion resistance, biofouling resistance, and antimicrobial resistance (*see Main Article: Copper in heat exchangers*). Copper has around twice the thermal conductivity of aluminium and faster, more efficient heat absorption. Its main applications are in industrial facilities, power plants, solar thermal water systems, HVAC systems, gas water heaters, forced air heating and cooling systems, geothermal heating and cooling, and electronic systems.

Copper is three times as dense^[5] and more expensive than aluminium.^[5] Copper heat sinks are machined and skived. Another method of manufacture is to solder the fins into the heat sink base. Aluminium heatsinks can be extruded, but the less ductile copper cannot.^{[7][8]}

Diamond is another heat sink material, and its thermal conductivity of 2000 W/m•K exceeds copper five-fold.^[9] In contrast to metals, where heat is conducted by delocalized electrons, lattice vibrations are responsible for diamond's very high thermal conductivity. For thermal management applications, the outstanding thermal conductivity and diffusivity of diamond is an essential. Nowadays synthetic diamond is used as submounts for high-power integrated circuits and laser diodes.

Composite materials can be used. Examples are a copper-tungsten pseudoalloy, AlSiC (silicon carbide in aluminium matrix), Dymalloy (diamond in copper-silver alloy matrix), and E-Material (beryllium oxide in beryllium matrix). Such materials are often used as substrates for chips, as their thermal expansion coefficient can be matched to ceramics and semiconductors.

Fin efficiency

Fin efficiency is one of the parameters which makes a higher thermal conductivity material important. A fin of a heat sink may be considered to be a flat plate with heat flowing in one end and being dissipated into the surrounding fluid as it travels to the other.^[10] As heat flows through the fin, the combination of the thermal resistance of the heat sink impeding the flow and the heat lost due to convection, the temperature of the fin and, therefore, the heat transfer to the fluid, will decrease from the base to the end of the fin. Fin efficiency is defined as the actual heat transferred by the fin, divided by the heat transfer were the fin to be isothermal (hypothetically the fin having infinite thermal conductivity). Equations 6 and 7 are applicable for straight fins.

$$\eta_f = \frac{\tanh(mL_c)}{mL_c} \quad [11] \quad (6)$$

$$mL_c = \sqrt{\frac{2h_f}{kt_f}} L_f \quad [11] \quad (7)$$

Where:

- h_f is the convection coefficient of the fin

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- Air: 10 to 100 W/(m²K)
- Water: 500 to 10,000 W/(m²K)
- k is the thermal conductivity of the fin material
 - Aluminium: 120 to 240 W/(m·K)
- L_f is the fin height (m)
- t_f is the fin thickness (m)

Fin efficiency is increased by decreasing the fin aspect ratio (making them thicker or shorter), or by using more conductive material (copper instead of aluminium, for example).

Spreading resistance

Another parameter that concerns the thermal conductivity of the heat sink material is spreading resistance. Spreading resistance occurs when thermal energy is transferred from a small area to a larger area in a substance with finite thermal conductivity. In a heat sink, this means that heat does not distribute uniformly through the heat sink base. The spreading resistance phenomenon is shown by how the heat travels from the heat source location and causes a large temperature gradient between the heat source and the edges of the heat sink. This means that some fins are at a lower temperature than if the heat source were uniform across the base of the heat sink. This nonuniformity increases the heat sink's effective thermal resistance.

To decrease the spreading resistance in the base of a heat sink:

- Increase the base thickness
- Choose a different material with better thermal conductivity
- Use a vapor chamber or heat pipe in the heat sink base.

Optimization (shape of the fins, location of fins, ...)

The shape of fins must be optimized to maximize heat transfer density where the space and the materials used for the finned surfaces are constraints.^{[12][13][14][15][16]}

Fin arrangements

A pin fin heat sink is a heat sink that has pins that extend from its base. The pins can be cylindrical, elliptical or square. A pin is by far one of the more common heat sink types available on the market. A second type of heat sink fin arrangement is the straight fin. These run the entire length of the heat sink. A variation on the straight fin heat sink is a cross cut heat sink. A straight fin heat sink is cut at regular intervals.

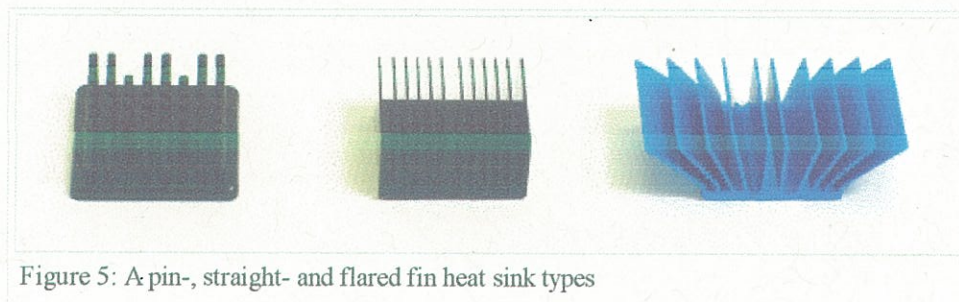


Figure 5: A pin-, straight- and flared fin heat sink types

In general, the more surface area a heat sink has, the better it works.^[2] However, this is not always true. The concept of a pin fin heat sink is to try to pack as much surface area into a given volume as possible.^[2] As well, it

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The heat transfer from the heat sink occurs by convection of the surrounding air, conduction through the air, and radiation.

Heat transfer by radiation is a function of both the heat sink temperature, and the temperature of the surroundings that the heat sink is optically coupled with. When both of these temperatures are on the order of 0 °C to 100 °C, the contribution of radiation compared to convection is generally small, and this factor is often neglected. In this case, finned heat sinks operating in either natural-convection or forced-flow will not be affected significantly by surface emissivity.

In situations where convection is low, such as a flat non-finned panel with low airflow, radiative cooling can be a significant factor. Here the surface properties may be an important design factor. Matte-black surfaces will radiate much more efficiently than shiny bare metal in the visible spectrum.^[27] A shiny metal surface has low emissivity. The emissivity of a material is tremendously frequency dependent, and is related to absorptivity (of which shiny metal surfaces have very little). For most materials, the emissivity in the visible spectrum is similar to the emissivity in the infrared spectrum; however there are exceptions, notably certain metal oxides that are used as "selective surfaces".

In a vacuum or in outer space, there is no convective heat transfer, thus in these environments, radiation is the only factor governing heat flow between the heat sink and the environment. For a satellite in space, a 100 °C (373 Kelvin) surface facing the sun will absorb a lot of radiant heat, because the sun's surface temperature is nearly 6000 Kelvin, whereas the same surface facing deep-space will radiate a lot of heat, since deep-space has an effective temperature of only a few Kelvin.

Engineering applications

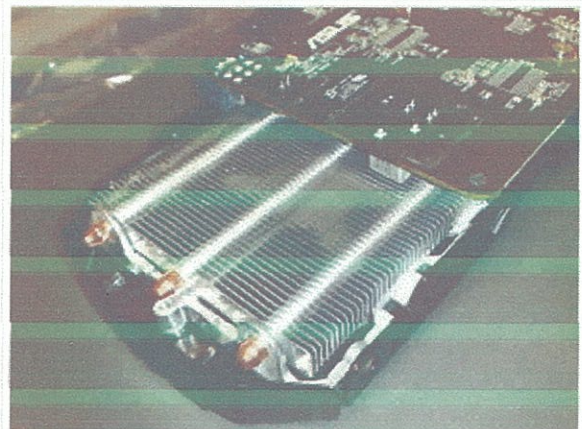
Microprocessor cooling

Heat dissipation is an unavoidable by-product of electronic devices and circuits.^[10] In general, the temperature of the device or component will depend on the thermal resistance from the component to the environment, and the heat dissipated by the component. To ensure that the component temperature does not overheat, a thermal engineer seeks to find an efficient heat transfer path from the device to the environment. The heat transfer path may be from the component to a printed circuit board (PCB), to a heat sink, to air flow provided by a fan, but in all instances, eventually to the environment.

Two additional design factors also influence the thermal/mechanical performance of the thermal design:

1. The method by which the heat sink is mounted on a component or processor. This will be discussed under the section *attachment methods*.
2. For each interface between two objects in contact with each other, there will be a temperature drop across the interface. For such composite systems, the temperature drop across the interface may be appreciable.^[11]

This temperature change may be attributed to what is known as the thermal contact resistance.^[11] *Thermal interface materials* (TIM) decrease the thermal contact resistance.



Cooling system of an Asus GTX-650 graphics card; three heat pipes are visible

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Attachment methods

As power dissipation of components increases and component package size decreases, thermal engineers must innovate to ensure components won't overheat. Devices that run cooler last longer. A heat sink design must fulfill both its thermal as well as its mechanical requirements. Concerning the latter, the component must remain in thermal contact with its heat sink with reasonable shock and vibration. The heat sink could be the copper foil of a circuit board, or else a separate heat sink mounted onto the component or circuit board. Attachment methods include thermally conductive tape or epoxy, wire-form z clips, flat spring clips, standoff spacers, and push pins with ends that expand after installing.

Thermally conductive tape

Thermally conductive tape is one of the most cost-effective heat sink attachment materials.^[28] It is suitable for low-mass heat sinks and for components with low power dissipation. It consists of a thermally conductive carrier material with a pressure-sensitive adhesive on each side.

This tape is applied to the base of the heat sink, which is then attached to the component. Following are factors that influence the performance of thermal tape:^[28]

1. Surfaces of both the component and heat sink must be clean, with no residue such as a film of silicone grease.
2. Preload pressure is essential to ensure good contact. Insufficient pressure results in areas of non-contact with trapped air, and results in higher-than-expected interface thermal resistance.
3. Thicker tapes tend to provide better "wettability" with uneven component surfaces. "Wettability" is the percentage area of contact of a tape on a component. Thicker tapes, however, have a higher thermal resistance than thinner tapes. From a design standpoint, it is best to strike a balance by selecting a tape thickness that provides maximum "wettability" with minimum thermal resistance.

Epoxy

Epoxy is more expensive than tape, but provides a greater mechanical bond between the heat sink and component, as well as improved thermal conductivity.^[28] The epoxy chosen must be formulated for this purpose. Most epoxies are two-part liquid formulations that must be thoroughly mixed before being applied to the heat sink, and before the heat sink is placed on the component. The epoxy is then cured for a specified time, which can vary from 2 hours to 48 hours. Faster cure time can be achieved at higher temperatures. The surfaces to which the epoxy is applied must be clean and free of any residue.

The epoxy bond between the heat sink and component is semi-permanent/permanent.^[28] This makes re-work very difficult and at times impossible. The most typical damage caused by rework is the separation of the component die heat spreader from its package.

Wire form Z-clips

More expensive than tape and epoxy, wire form z-clips attach heat sinks mechanically. To use the z-clips, the



Figure 6: Roll of thermally conductive tape.

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